NISTIR 6890

Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NISTIR 6890

Fire Resistance Determination and Performance Prediction Research Needs Workshop: Proceedings

William Grosshandler
Editor
Building and Fire Research Laboratory

September 2002

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

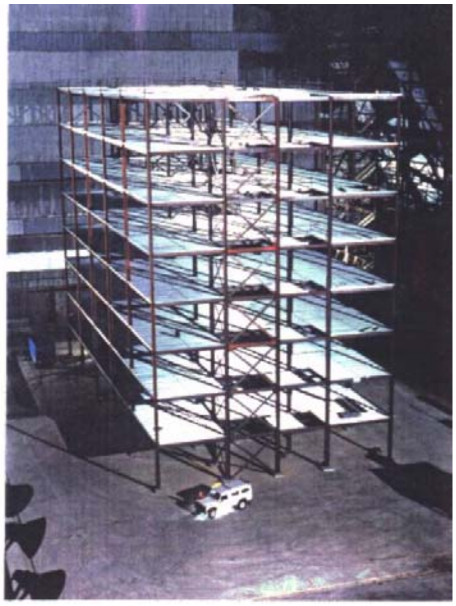

Figure 4. Full-scale steel structure built in Cardington Laboratory (left), and during a test fire (Usmani)

FIRE TESTING AND SIMULATION

H. Baum

The research needs from a fire modeler's perspective were stated succinctly by Baum. The first need is associated with defining the building. While conceptually straightforward, the large amount of data available to describe a modern building and the differing ways that these data are used for design, operations, and maintenance overwhelms the individual interested in predicting fire resistance performance, leading to great inefficiencies in the calculations and limiting their value. An efficient way to generate an electronic database that can be accessed seamlessly for multiple purposes is critical. The detail has to be sufficient to capture the location and operations of the HVAC systems, elevators and stairways. The second need is to develop a better understanding of the burning behavior of the contents of modern buildings, including complex shaped objects (e.g., real furniture), libraries and paper files. Being able to predict the occurrence of fire-induced geometry changes is the third primary need, specifically windows breaking and the warping/penetration of partitions (walls and floors).

A. Sarofim and P. Smith

An overview of the Center for the Simulation of Accidental Fires and Explosions (C-SAFE) located at the University of Utah was given by Sarofim and Smith (Appendix III. E). C-SAFE is allied with the Accelerated Strategic Computing Initiative (ASCI) to develop (unclassified) simulation science in support of the DOE defense program laboratories to safeguard the U.S. nuclear stockpile. C-SAFE is focused on the science-based tools for numerical simulation of accidental fires and explosions, within the context of handling and storing highly flammable material. The accident scenario to be simulated is a conventional high explosive material in a metal container of arbitrary shape, size and location within an arbitrary, sooting hydrocarbon pool fire. Following an assumed ignition of the liquid fuel, the calculations are made of the fire spread, the dynamics of the container, high energy transformations, and conditions that lead to accidental detonation. An example was provided of a calculation of a 10 m diameter heptane pool fire in a $(50\ m)^3$ domain. With 3.4 million computational cells and 6800 time steps, the calculation took 18 h to complete on the Los Alamos Nirvana computer (500 processors). The challenge for the Center is to make optimum use of the increasing number of processors to allow finer spatial resolution. Problem areas for the integrated calculation exist at the interfaces between the various phases, communication among the multiple scientific disciplines involved and with the ultimate user, and all aspects of data management (transfer, storage, mining). Lessons from Sarofim and Smith that may bear on predicting the fire resistance of structures include the encouragement to consider interdisciplinary approaches on cross-cutting issues, in particular a close collaboration with software engineers and computer scientists. "Amphibians" are needed to bridge disciplinary gaps, and the importance of communication cannot be overstated. The C-SAFE program has advanced the state of computational chemistry to predict properties, mechanisms and kinetics, and more detailed chemistry and fluid mechanics can be included in massively parallel computations. The material point methods show promise for handling large deformations and the break up of structures. Sarofim and Smith concluded by emphasizing the importance of experiments for guiding and validating the computations.

A. Usmani

An eight story steel structure, shown in Figure 4, was built in Cardington, England in the mid 1990s [10] to examine the behavior of individual elements and the structural frame when exposed to various fire environments. The impetus for the full-scale testing was to demonstrate that the requirements for structural design fire safety were overly conservative. The Cardington tests have improved our understanding of structural behavior in fire, produced data for validating computer models. The new understanding of composite framed structure behavior in fire, so generated, may lead eventually to more rational design methods, and could reduce the cost of steel fire protection.

Usmani (Appendix III. G) described the challenge of numerically modeling the response of the Cardington structure to different fire loads. ABAQUS [11, 12] was used to examine a large number of structural arrangements and the details of modeling and subsequent interpretations of behavior are too voluminous to present here. However, interested readers can find many reports and other documentation containing substantial details of this work at

http://www.civ.ed.ac.uk/research/fire/project/main.html.

Very briefly, this work revealed the following lessons for whole structure behavior in fire:

- restraint to thermal strain dominates behavior of the composite beam and slab system
- conventional loading contribution to overall behavior is low
- the results show low sensitivity to variations in strength and stiffness properties of steel
- at large deflections tensile membrane action in the spans and compressive membrane action near the perimeter supports of floor slabs were observed
- thermal strains automatically produce a beneficial load-carrying shape in tensile membrane action for slabs without large and damaging mechanical strains
- the load capacity can be further enhanced by thermal pre-stressing
- local buckling of the lower flange always occurred but was not found to be a detrimental mechanism

A simple analysis will reveal that in a member restrained from lateral translation, as the mean temperature increases, compression occurs, but as the through-depth temperature gradient increases, tension occurs. The former scenario is most likely in a slow growing, protracted fire, while the latter results from a rapidly growing, short duration fire. Frames smaller than the Cardington structure may have fewer redundant paths, and the fires could extend over the entire floor. By the same token, large compartments that may be a part of a very large frame may behave quite differently because of the nature of the fire (spreading with local flashover perhaps) leading to significantly different structural response. To enable reliable tensile membrane mechanisms, it is necessary that the floor slab reinforcement is anchored at the compartment perimeter, with interior continuity provided by lapping reinforcement. Edge and corner compartments have discontinuous edges that may or may not have fire protection. Unprotected edges will provide considerably lower anchorage to tensile membrane forces, therefore protecting edge beams seems worthwhile as a means to anchor membrane forces and to protect cladding. Further 3-D modeling using DIANA was conducted to examine the impact of these variables on the structure and the results produced similar conclusions.

The key conclusions from this work are that the structural response to a fire depends upon the rate of heating as well as the temperature of the structure, and that different fires can produce very different stress/strain patterns in composite floor systems. This is because most of the pre-failure response of structural members depends upon the two geometric effects produced by heating, a mean temperature increase and a mean thermal gradient. The material effects of reduction in strength and stiffness begin to dominate just before failure.

Further research was suggested by Usmani to establish the worst case fire scenario on the basis of the maximum structural damage it would inflict on the building (in addition to other life safety issues such as smoke movement and egress, the worst case scenario(s) for these may be quite different). This would require new scientifically based and practical analysis methods for reliable prediction of structural damage against a given heating regime. Research is also required to properly include (in a risk-based framework), extreme fire events as limit states, (which should be the basis of all structural designs). Tall buildings with long evacuation times require special consideration to ensure that localized collapse does not lead to overall progressive collapse. Other questions that need further research are: Are floor slab failures ductile or brittle? Can one generalize that a short and hot fire places a more severe load on the structure than a sustained, less intense fire (or vice versa)? How important is it to model connections, the cooling process, and the integrity of non-load bearing compartment boundaries? A final provocative question posed (but not answered) by Usmani is, How does one define failure?

In terms of the fundamental structural and solid mechanics research required in the context of understanding structural response to extreme events, perhaps the most important research need is as follows. Most failures in large redundant structures have roots in local “seed” events (such as a crack or fracture) that grow without being arrested and cause progressive global collapse. Many local events in a large redundant structure will occur as load redistribution mechanisms and will be self-limiting under the overall equilibrium and compatibility constraints. A thorough understanding of the development of local structural phenomena into events that threaten global structural stability/integrity should be one of the main research objectives.

V. Kodur

The positive attributes of high strength concrete for buildings and columns make it an attractive material, but its high density and low porosity make it susceptible to spalling under fire conditions. Since an intended benefit of concrete is the elimination of additional fire protection, methods are required to ensure the fire safety of high strength concrete. However, there are currently no guidelines for the exposure of high strength concrete to fire. Test methods for evaluating the fire resistance of large-scale structural systems were described by Kodur (Appendix III. H), and used to highlight the differences in performance between high and normal strength concrete.

Columns of both types of concrete were examined, with size, load intensity, fiber reinforcement, fire intensity, and reinforcement configuration the independent variables. The specimens were full-scale and designed according to code, and tested according to the protocol in ASTM E119 (see Figure 5). Column temperatures, deflections and degree of spalling were the dependent variables. The primary observations during the tests were that spalling was not significant in the first 30 minutes, and that using 135° (as opposed to 90°) column-ties reduces early spalling to a minimum. Within 2 h, hair line cracks appear, widen at corners, and lead to chunks of concrete dropping off for the 90° reinforcing bar ties. Failure occurs when the ties open up and the rebar buckles. The 135° ties remain superior all the way through the test. The normal strength concrete, for comparison, failed only locally, the ties did not open up nor rebar buckle, and less spalling occurred.

Figure 5. Comparison between normal strength concrete (left) and high strength concrete (right) after ASTM E119 column test.

Figure 6. Photograph of modern floor testing furnace (Kodur)

Kodur summarized the factors that influence fire performance of concrete: compressive strength, reinforcement layout, moisture content, concrete density, heating rate, aggregate type, load intensity and type, and fiber reinforcement. The major factors that enhance spalling and decrease fire resistance are higher concrete strength and higher loads; factors that reduce spalling and increase fire resistance are closer tie spacing, 135° ties, use of carbon aggregate, and use of reinforcing fibers. The experimental work conducted at CNRC was complimented by numerical studies of the factors influencing behavior, using thermal and mechanical properties measured at elevated temperatures, to develop design equations for fire resistant structures.

For the future, Kodur emphasized the need for realistic conditions when assessing fire resistance, the need for analytical tools and specified fire scenarios, with validated models, design fires and material properties. To be ready for performance-based codes, the industry must have suitable calculation methods, software packages and design guides. High performing materials must satisfy fire resistance criteria, and practical and cost-effective solutions to overcome current shortcomings are necessary.

U. Wickstrom

The need for improved fire testing in combination with calculations was the theme stressed by Wickstrom (Appendix III. I). When analyzing the performance of structures exposed to fires, one needs to consider the fire development (design fire), heat transfer to fire exposed structures, temperature development in the structures, and the resulting mechanical behavior of the structures. To improve fire resistance design, standard methods for measuring thermal and mechanical properties of structural and protective materials must be developed. Techniques for improving furnace testing and for monitoring deformation properties during the test are also required. Two specific techniques put forth by Wickstrom are the transient plane source, heat transmission, thermal diffusivity (TPS) apparatus and the plate thermometer. The former consists of a thin heater that is sandwiched between flat sections of the fire protection material under investigation. By following the temperature as a function of heat input, position, and time, key thermal properties can be generated. The plate thermometer can be used to monitor and control the temperature in the furnace (e.g., ISO 834 or ASTM E119). The benefit of the plate thermometer is that it allows one to calculate the true structural temperature in close agreement with the measured structural temperature (see Figure 7), in contrast to the standard shielded thermocouple. While no techniques were proposed for measuring deflection during the test, Wickstrom emphasized that such data are essential to relate calculated behavior to actual expected behavior.

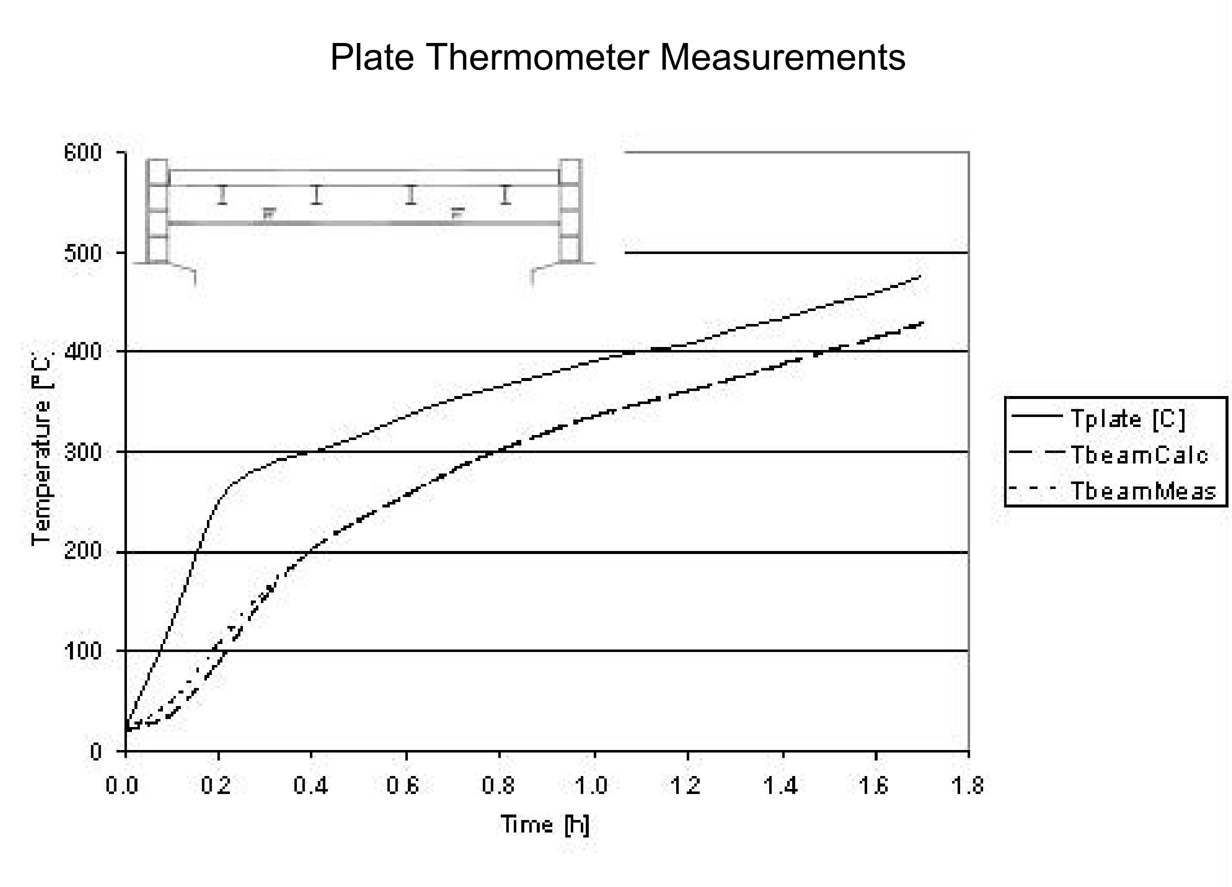

Figure 7. Temperature measurements in floor assembly furnace test, comparing the plate thermometer to the calculated temperature.

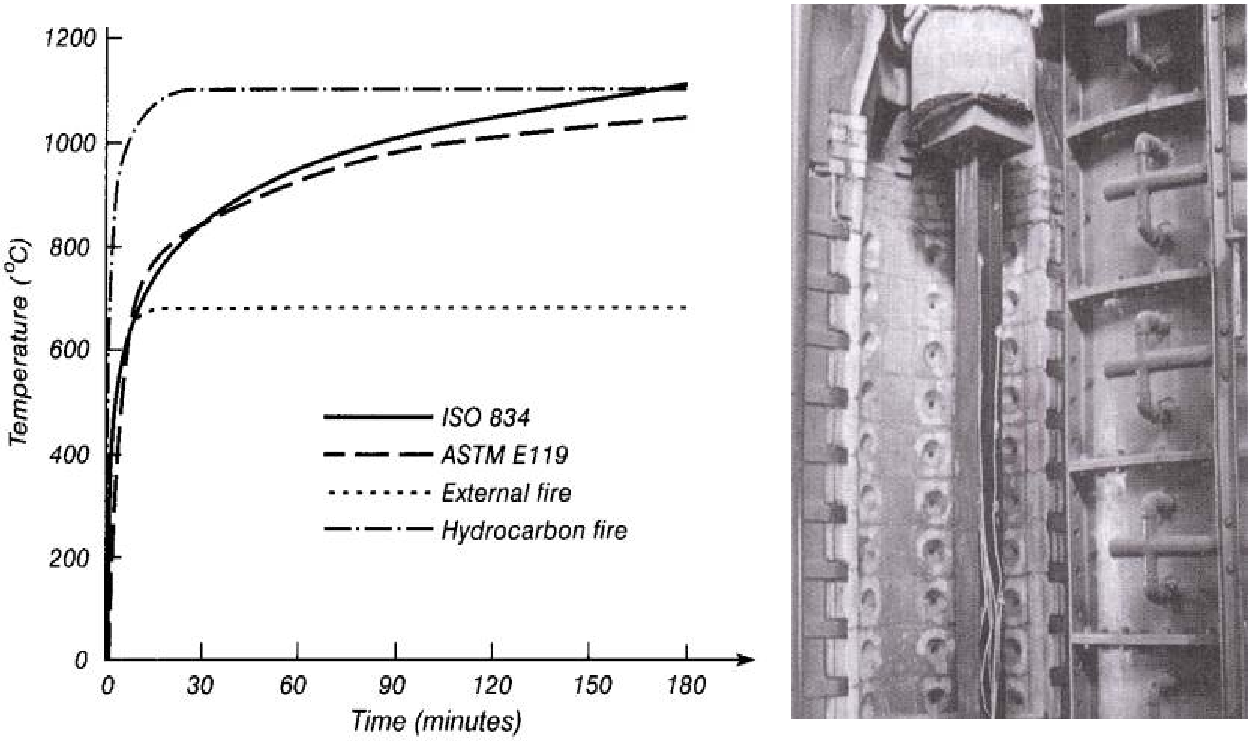

Figure 8. Alternative temperature-time curves for fire resistance tests (left), and a photograph of a steel column ready for testing in the furnace.

FIRE RESISTANT MATERIALS

R.B. Williamson

Williamson (Appendix III. K) briefed the participants on the history of fire protection of structural steel and the materials used for that purpose. Dating back to the 1898 Home Life Fire in New York City, a new approach to high rise safety began emerging that required buildings to be constructed of columns, floors, walls and other elements that were fire resistive, defined as the ability of an element to withstand the effects of fire for a specified period of time without loss of its fire separating or load bearing function. This ability was determined by exposure in a furnace to sustained high temperatures. Various temperature-time curves are used today, depending upon the country and application. Figure 8 compares the ISO 834 test, the hydrocarbon fire (ASTM E1529), and external fire exposures to the standard ASTM E119 curve (also shown in Figure 1). A column instrumented for a test is shown on the right.

The first materials used for fire proofing in the early 20th century were traditional construction materials such as masonry or concrete, which led to substantial labor costs and excessive weights. Gypsum-based systems such as wire lath and plaster systems came on the market thereafter, but these also suffered labor and weight penalties. Like concrete, these systems derived